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Experimental Results From a 2kW Brayton Power Conversion Unit

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January 2003

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Abstract. This paper presents experimental test results from operation of a 2 kWe Brayton power conversion unit. The Brayton converter was developed for a solar dynamic power system flight experiment planned for the Mir Space Station in 1997. The flight experiment was cancelled, but the converter was tested at Glenn Research Center as part of the Solar Dynamic Ground Test Demonstration system which included a solar concentrator, heat receiver, and space radiator. In preparation for the current testing, the heat receiver was removed and replaced with an electrical resistance heater, simulating the thermal input of a steady-state nuclear source. The converter was operated over a full range of thermal input power levels and rotor speeds to generate an overall performance map. The converter unit will serve as the centerpiece of a Nuclear Electric Propulsion Testbed at Glenn. Future potential uses for the Testbed include high voltage electrical controller development, integrated electric thruster testing and advanced radiator demonstration testing to help guide high power Brayton technology development for NEP.

INTRODUCTION

Closed Brayton cycle conversion technology has been identified as an excellent candidate for Nuclear Electric Propulsion (NEP) power conversion systems (Mason, 2001) (Mason et al., 2002). Advantages include high efficiency, long life, and high power density for power levels from about 10 kWe to 1 MWe, and beyond. An additional benefit for Brayton is the potential for the alternator to deliver very high voltage as required by the electric thrusters, minimizing the mass and power losses associated with power management and distribution (PMAD).

In order to accelerate Brayton technology development for NEP, Glenn Research Center (GRC) has initiated a low power, NEP Testbed activity which utilizes an existing 2 kWe Brayton Power Conversion Unit (PCU) from previous solar dynamic technology efforts (Shaltens, Mason, 1996, 1999). The PCU includes a turboalternator, recuperator, and gas cooler connected by gas ducts. The rotating assembly is supported by gas foil bearings and consists of a turbine, compressor, thrust rotor, and alternator on a single shaft as shown in figure 1. The completed turboalternator unit is shown in figure 2. The Brayton PCU will serve as the centerpiece of the NEP Testbed allowing future investigations of operational control methods, higher voltage PMAD, electric thruster interactions, and advanced radiators.

The existing 2 kWe Brayton PCU was modified by removing the original solar dynamic heat receiver and retrofitting an electrical resistance heater to simulate the thermal input of a steady-state nuclear source. A series of tests were performed between June and August of 2002 that resulted in a total PCU operational time of 23.7 hours. An initial test sequence on June 17 determined that the reconfigured unit was fully operational. Ensuing tests provided the operational data needed to characterize PCU performance over its intended operating range.

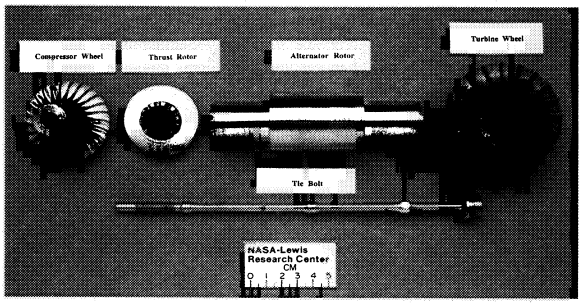

FIGURE 1. Turboalternator Rotating Assembly.

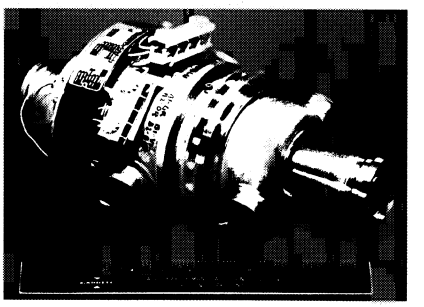

FIGURE 2. Turboalternator Unit.

TEST SETUP

The testing was performed in Vacuum Facility 6 (VF6) of building 301 at the NASA Glenn Research Center in Cleveland, Ohio. The overall test setup is shown in figure 3. The PCU is contained in the 3 meter test port at VF6. All electrical, instrumentation, and fluid connections are provided to the unit via tank wall feedthroughs. The three instrumentation racks on the right hand side of figure 3 house the PMAD, data acquisition, and test support equipment control electronics. Additional equipment supporting the Testbed operation includes the alternator test rig, gas charging cart, gas heater power supply, and PCU chiller.

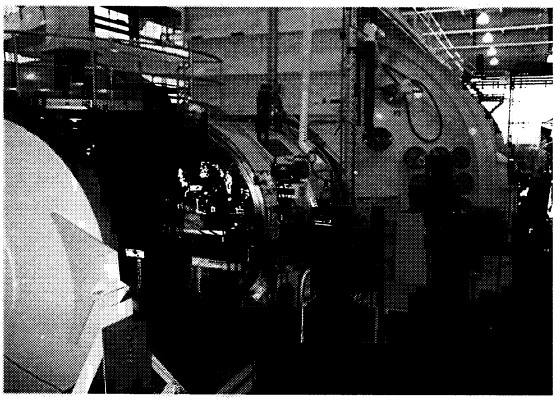

FIGURE 3. Brayton Testbed at GRC Vacuum Facility 6.

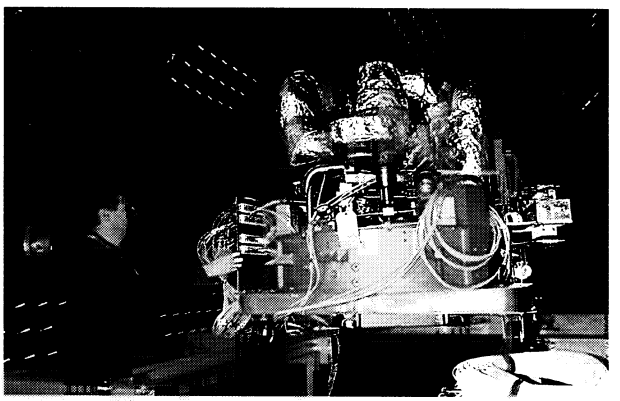

FIGURE 4. Brayton Power Conversion Unit.

Figure 4 shows the Brayton PCU as installed in the VF6 test port. The PCU produces AC power which is rectified to 120V DC power by the PMAD unit. Test instrumentation includes 32 type K thermocouples, 8 pressure transducers, alternator voltage and current, DC load voltage and current, coolant flow rate, rotor speed, and heater electrical power. The entire PCU is covered in Multi-Foil Insulation (MFI) and operates in a rough vacuum environment ($\sim 1 \times 10^{-3}$ torr) to minimize heat transfer to the environment.

Gas Heater

The PCU gas heater consists of three resistive elements in series that are inserted into a shell and tube heat exchanger. The Si-C resistor elements are capable of withstanding sustained temperatures up to 1923K. These heating elements do not come into contact with the working fluid and heat the inner surface of the heater exclusively by radiation. This shell and tube heater is covered with MFI to minimize heat loss. The only area not covered with

this insulation is where the electrical leads are attached. The gas heater assembly is shown in figure 5 before MFI was applied.

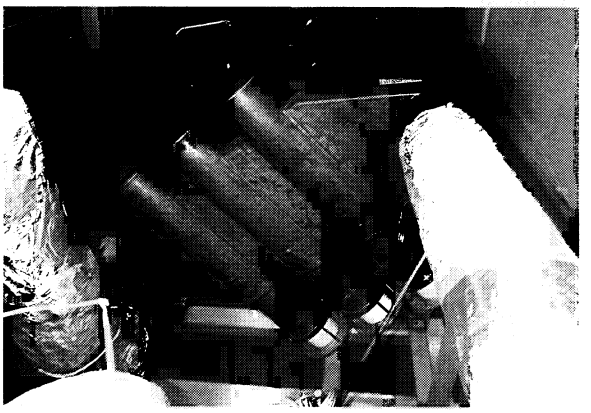

FIGURE 5. Gas Heater Assembly Before Insulation.

The electrical heater has a dedicated 480V power supply that isolates it electrically from the remainder of the test equipment. The heater utilizes an industrial style Proportional-Integral-Derivative (PID) controller providing constant power to the resistive elements as specified by the test operator.

Power Management and Distribution

The PMAD electrical control system performs the functions of alternator output voltage rectification and regulation, rotor speed control, and PCU startup. The control system operates autonomously except for operator commands to begin and end motor starting. An inverter power supply provides electrical input to the alternator for startup motoring. The PMAD control system also provides redundant and automatic overspeed shutdown protection for the turboalternator.

The Brayton PCU includes a 3 phase permanent magnet alternator (Mason, Shaltens, 1997) that produces an output voltage proportional to the alternator speed, and inversely proportional to the applied load. The output voltage is rectified with a 3 phase full wave bridge, and then filtered to provide a smooth DC output of nominally 120V. At light loads the speed of the alternator is reduced to keep the output of the rectifier from exceeding 120V. At higher loads the alternator output drops to about 100V, and a boost converter circuit is used to increase the output of the rectifier back to 120V.

The electrical load on the alternator is controlled to regulate the rotational speed. If the load torque is equal to the torque supplied by the rotor, the speed will be constant. Increasing the alternator loading decreases the speed, and decreasing the alternator loading increases the speed. This technique is called parasitic load speed control. The amount of parasitic load applied to the machine is controlled, based on the speed setpoint specified by the test operator. The power in the parasitic load is then dissipated as waste heat. Power measurements were collected using a commercial AC power meter.

The design and assembly of the PMAD electronics rack was completed in-house at GRC. The alternator test rig (ATR) provided a critical tool in developing the overall electrical design and verifying the functionality. The ATR includes an air-driven turbine attached to a permanent magnet alternator which duplicates the PCU alternator's electrical characteristics to assist in troubleshooting of the PMAD rack without subjecting the PCU to unnecessary risk.

PCU Chiller

Waste heat is removed from the PCU working fluid by the gas cooler and rejected into a 50% ethylene glycol 50% water mixture. A commercial chiller located in the test facility basement provided the final system coolant heat rejection. The chiller provides coolant flow rates of approximately 3 gallons per minute at a controlled setpoint of 273K for heat loads up to about 4.5 kWt. The coolant supply temperature is the major influence on compressor inlet gas temperature. At higher heat loads, the coolant supply temperature and compressor inlet temperature experienced modest increases of 5 to 15K.

Data Acquisition and Control

Test data was acquired using a commercial datalogger connected to a desktop computer. The computer software performed real time calculations of heat input and heat rejected by the PCU, cycle efficiency, compressor and turbine efficiencies, recuperator effectiveness and mass flow rate. A Graphical User Interface (GUI) was provided showing all pressures, temperatures, power levels, voltages, currents, flow rates, and calculated values, as shown in figure 6. Test data was concurrently saved to data files for post processing.

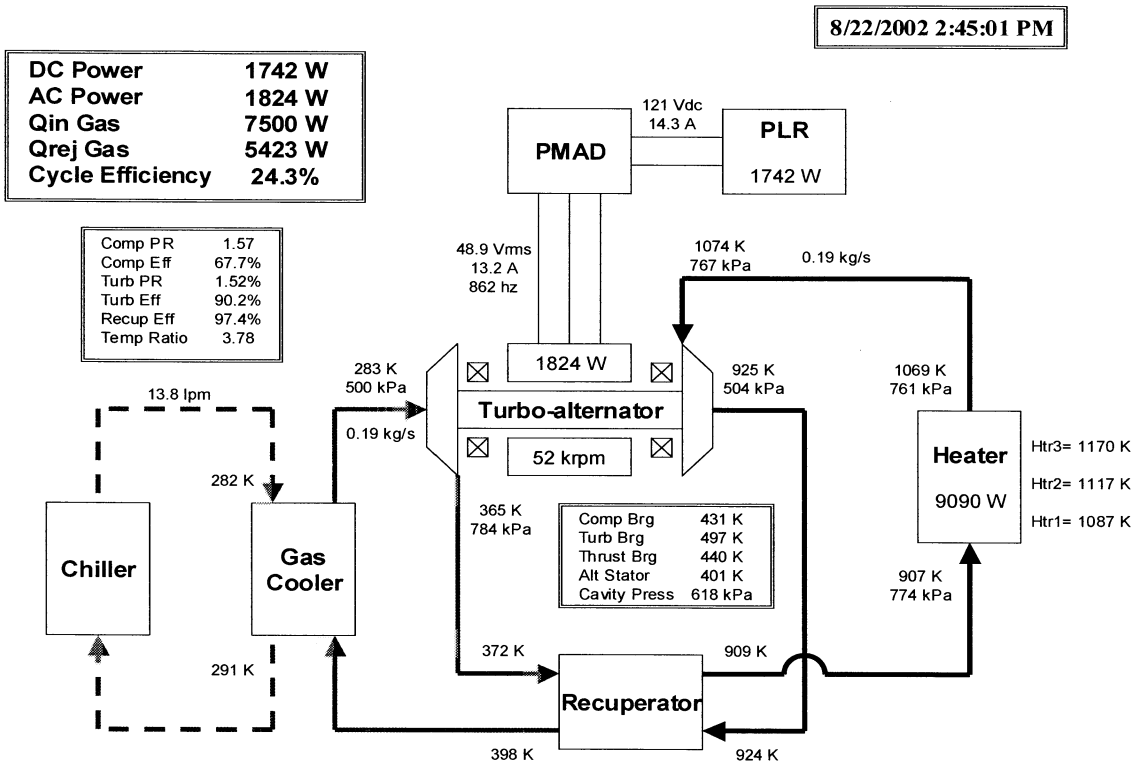

FIGURE 6. Graphical User Interface.

A second electronics rack houses operator interface control panels for the gas heater power supply, PCU chiller, and PCU bypass valves. The bypass valves are provided to isolate the compressor and turbine gas flow paths during alternator motoring, allowing faster and more efficient startups.

PCU Gas Charging Cart

A gas charging system provides the capability to fill and maintain the working fluid charge. The Brayton PCU uses a 37% molar helium 63% molar xenon gas mixture working fluid, selected to optimize overall cycle efficiency. The mixture has a molecular weight of 83.8. Initially, the PCU was charged to 260 kPa turbine inlet pressure for the June 17 initial test run. The inlet pressure reached 530 kPa at 51000 rpm. It was decided to increase the initial charge pressure to allow for a higher system power capability. The unit was pre-charged to 330 kPa for the June 24 test. The turbine inlet pressure reached 743 kPa at 52000 rpm during this run. This pre-run charge pressure was maintained on all subsequent tests.

TEST MATRIX

There are two primary variables used in operating the Brayton PCU: heater input power and rotor speed. The PCU was operated at 9 different heater power levels and 6 different rotor speeds resulting in 21 unique steady-state test points.

The general operating procedure included heating the gas to about 475K, and then motoring the alternator to circulate the gas until thermal conditions were suitable to sustain the thermodynamic cycle, allowing switchover to generate mode. The average alternator motoring time to achieve self-sufficient operation was about 10 minutes. After startup, heater power level and rotor speed setpoints were selected by the operator to achieve a particular test point. Test points were declared when steady state operation of the PCU was achieved, defined as less than 1K change in the turbine inlet temperature over a 5 minute period. Regulated DC Voltage was maintained at 120V for all of the tested heater power level and rotor speed combinations.

TEST RESULTS

The PCU was started and stopped a total 20 times. A total of 14 alternator motoring tests were used to troubleshoot the startup motoring operation. The remaining 6 start/stop cycles were fully operational test runs providing results in accordance with the test matrix.

Alternator Motoring tests

The PCU motor was initially wired in accordance with drawings available from the Solar Dynamic configuration. During the initial starts, the motor would only move a portion of a revolution or not at all. Re-phasing the alternator and speed sensors, and electrically retarding the sensors 60° appeared to correct the problem, but the alternator was actually running in reverse. This was first noticed as the temperatures in the PCU were increasing in the wrong direction during motor start. For example, the heater inlet was rising in temperature instead of dropping. The motor phases and angle sensors were rewired and a 60° sensor advance was added to correct this problem. Correct motor operation was confirmed by the observing correct gas flow direction.

Electrical Power Output

After an initial series of tests that determined operational limits, PCU performance was fully characterized at 48000 rpm and 52000 rpm for a variety of gas heater power levels. Cycle temperature ratio (turbine inlet divided by compressor inlet temperature) provides an effective dependent parameter for evaluating PCU and component performance. Figure 7 shows the linear relationship between AC power output and temperature ratio. Testing demonstrated a maximum steady-state AC power output of 1835 watts at a gas heater power of 9000 watts and a rotor speed of 52000 rpm. This equates to a net DC power output of 1750 watts, corresponding to a PMAD efficiency of 95%.

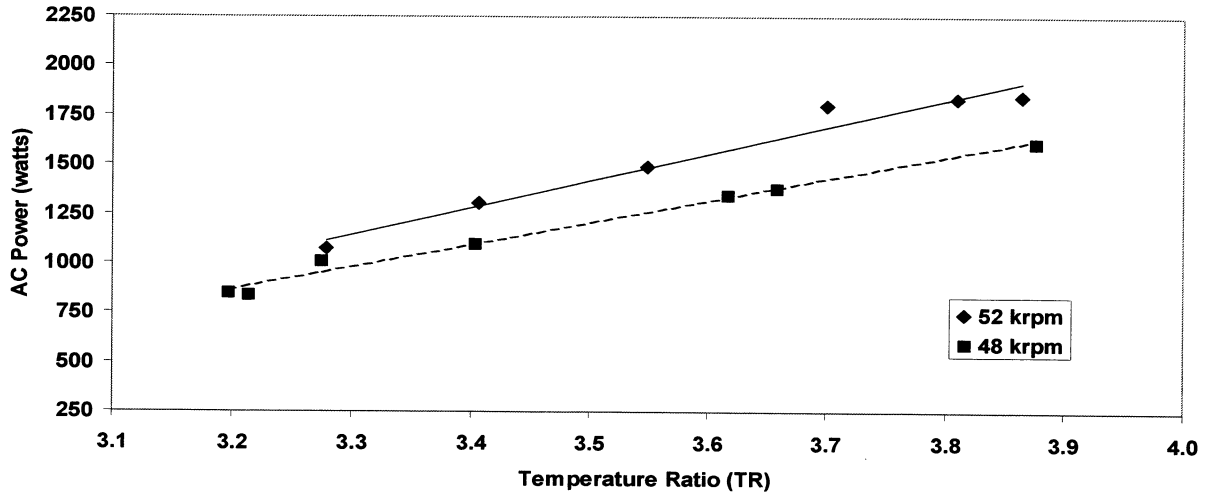

FIGURE 7. AC Power Output.

Cycle Efficiency

Figure 8 shows the relationship between cycle efficiency and temperature ratio for the 48000 and 52000 rpm rotor speed setpoints. Rotor speed has a negligible effect on cycle efficiency as indicated by the similarity of the two line fits. Testing demonstrated a maximum steady-state cycle efficiency of 24% at a gas electrical heater power of 9000 watts and a rotor speed of 52000 rpm.

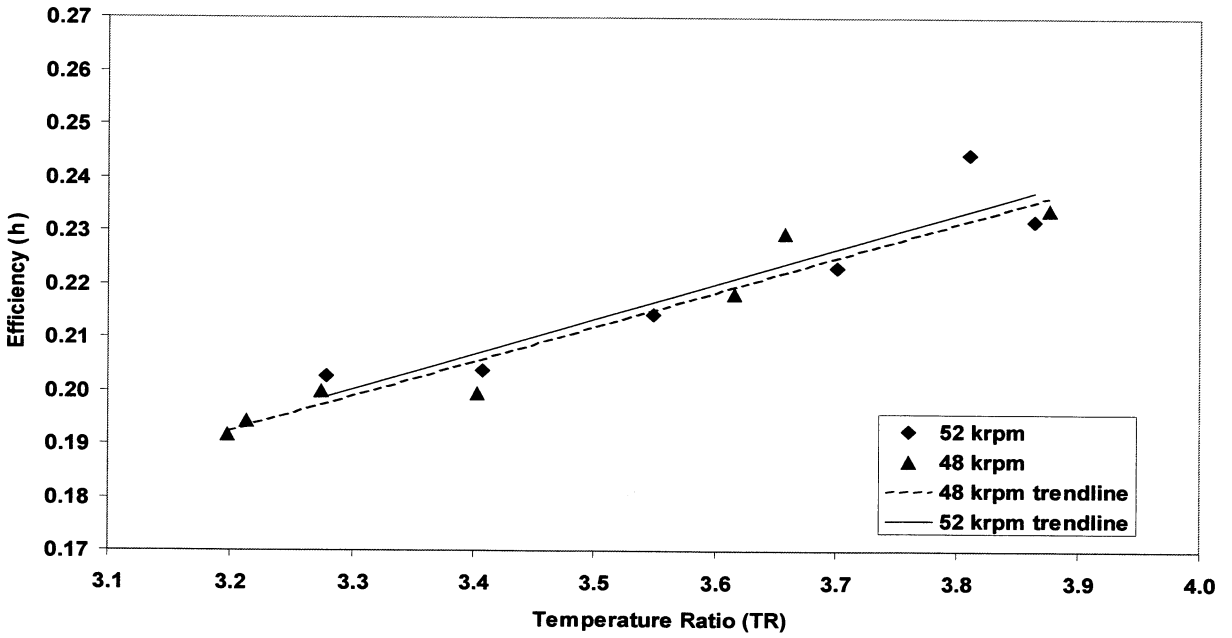

FIGURE 8. Cycle Efficiency.

Pressure ratios and pressure loss fractions have a dramatic effect on cycle efficiency. At 52000 rpm, the compressor pressure ratio was about 1.57 and the turbine pressure ratio was about 1.52. This corresponds to a pressure loss fraction of 97%. Component gas pressure losses for the maximum power test point at 52000 rpm were 0.8% for the heater, 1.4% for high pressure side of the recuperator, and 0.8% for the combined pressure loss through the low pressure side of the recuperator and gas cooler.

Component Efficiencies

Figure 9 shows the relationship of turbine and compressor efficiency, and recuperator effectiveness versus temperature ratio at 52000 rpm. As shown, turbine efficiency increases and compressor efficiency and recuperator effectiveness decrease with increasing temperature ratio. Testing obtained a maximum steady-state turbine efficiency of 96% and a maximum steady-state compressor efficiency of 70%. The maximum steady-state recuperator effectiveness was 98%.

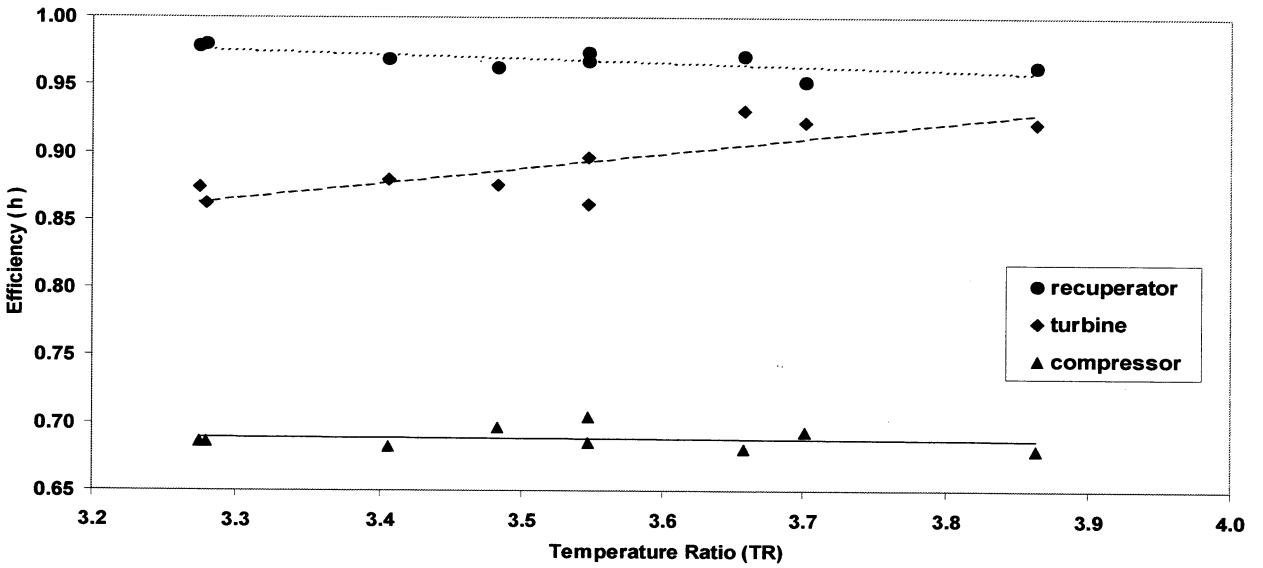

FIGURE 9. Turbine, Compressor Efficiency and Recuperator Effectiveness vs. Temperature Ratio at 52000 rpm.

PCU Shutdown

PCU shutdown is initiated by turning off the electrical heaters. There is enough residual thermal energy to continue operating the unit for approximately 30 minutes. After the measured power output has dropped to zero, the bypass valves are opened and the time for the unit to stop is measured. This measurement is called rolldown time which provides a useful parameter for assessing the health of the foil bearings. Rolldown times were consistently around 25 seconds, indicating that the foil bearings are still in good condition despite their long term storage following the Solar Dynamic testing and current operation during this series of tests.

TESTING ISSUES

Vacuum arcing occurred several times during startup of the electrical gas heater. This arcing tripped the circuit breaker in the 480V heater power supply. No other systems were affected. Arcing only transpired during heater restart following a vacuum cooldown. Video of the heater during restart showed the arc initiating from near the electrical leads. Arcing did not occur when the chamber was re-pressurized between tests. After some investigation, it was determined that the unit was operating at an unfavorable combination of heater voltage and

vacuum level that is susceptible to arcing. Measures are being pursued which should eliminate this phenomenon. The first measure will cover the electrical power leads with ceramic standoffs and seal them with high temperature ceramic putty. The second measure is to filter the heater power supply thus reducing the sharp current transients resulting from the waveform chopping used to control heater power.

CONCLUSION

The reconfigured Brayton PCU has been shown to operate efficiently and reliably in a vacuum environment. Rotor speed was dependably maintained at setpoint conditions and voltage was consistently regulated at 120V DC over the entire range of speeds and heat inputs. Power output and cycle efficiency were characterized over the full heater input power and rotor speed range. The Brayton PCU is ready to provide power for follow-on testing in support of NEP technology development.

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